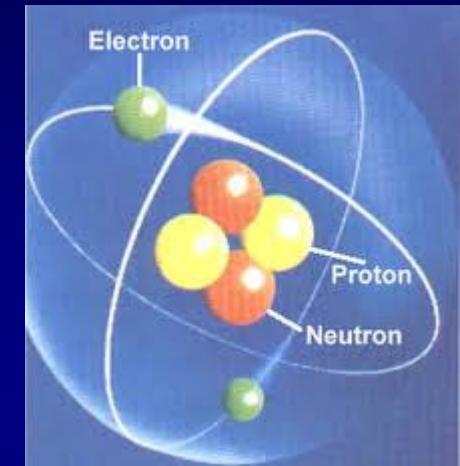


# Chapter 3

# HP Fundamentals

# Objectives

- **Describe basic atomic structure**
- **Describe the atomic number, neutron number and atomic mass**
- **Define the terms isotope, ionization, radiation and radioactive material**
- **Discuss the difference between radiation and contamination**
- **Discuss the particulate and non-particulate types of radiation**



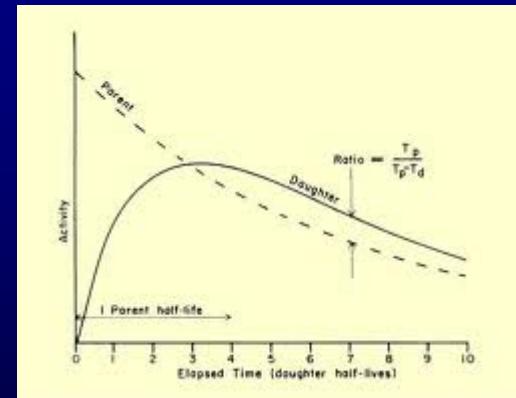
# Objectives

- Explain alpha, beta, positron and gamma decay
- Define the terms activity and half-life
- Define decay constant and relate it to activity
- Utilize the decay equation to calculate the number of atoms in a sample or activity of a sample



# Objectives

- Define and calculate specific activity
- Define serial decay
- Discuss the types of radioactive equilibrium



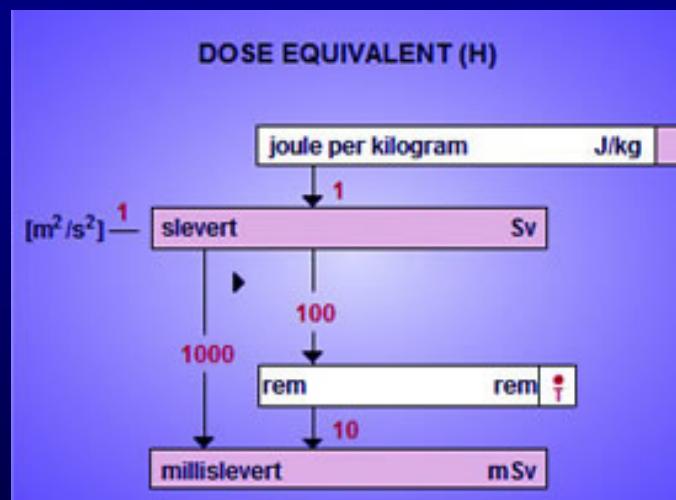
# Objectives

- Discuss the concept of exposure
- State three fundamental limitations of the roentgen
- Define absorbed dose and its traditional and SI units
- Discuss limitations of the rad
- Define the term quality factor



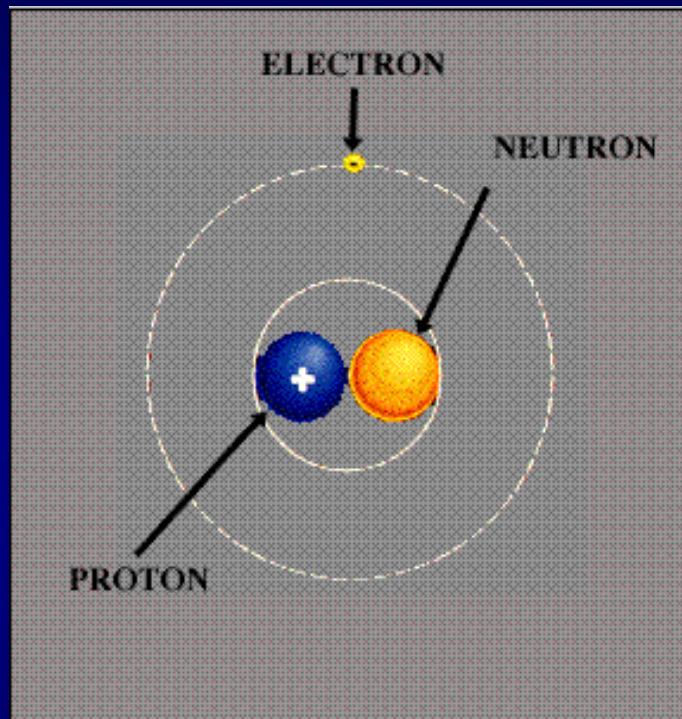
# Objectives

- Define the term dose equivalent including the SI and conventional units
- State the relationship between roentgen, rad, and rem for photon dose to human tissue



# Atomic Structure

- Atoms have orbital electrons, which have a negative charge, and a nucleus comprised of neutrons and protons.
- Protons have a positive charge. Typically there is an orbital electron for each proton in the nucleus.
- The element is determined by the number of protons in the nucleus.



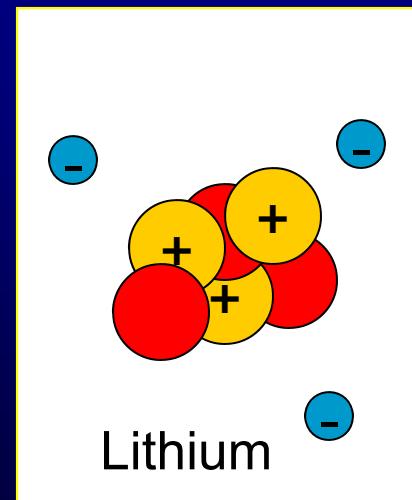
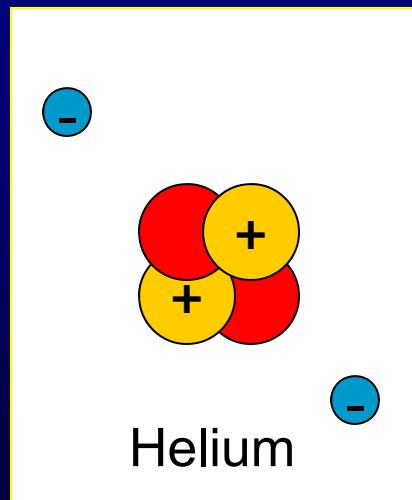
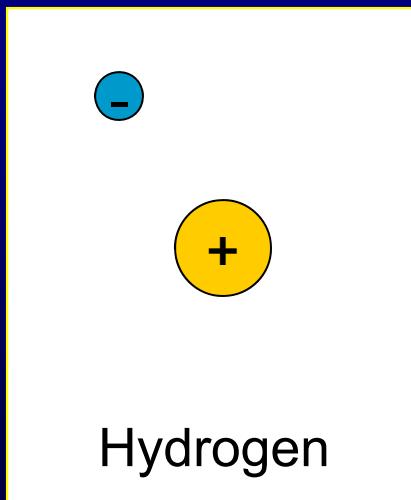
# Elements



"Of course the elements are earth, water, fire and air. But what about uranium? Surely you can't ignore uranium."

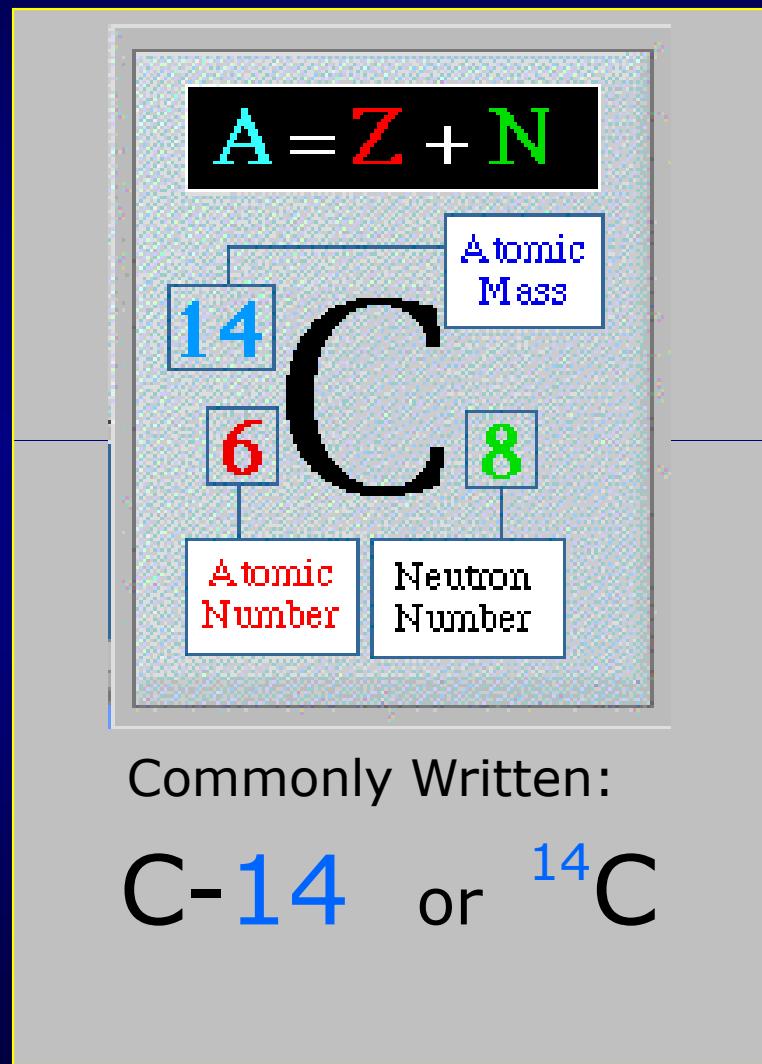
# Atomic Structure

- A hydrogen (H) atom has one proton in its nucleus and one orbital electron.
- A helium (He) atom has two protons in its nucleus, so it has two electrons...and so on...
- All electrically neutral atoms have one negative electron for each positive proton in the nucleus.



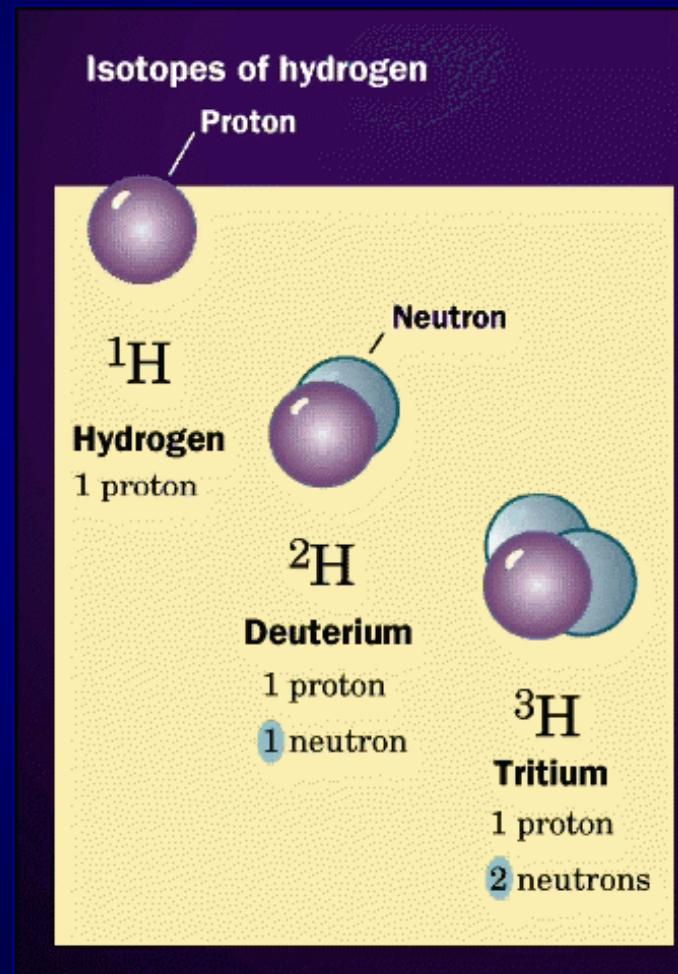
# Nuclear Notation

- The number of protons in the nucleus is called the atomic number, Z, which determines the element.
- The neutron number, N, is the number of neutrons in the nucleus.
- The atomic mass, A, is the sum of the atomic number, Z, and neutron number, N.



# Definitions

- Atoms with the same number of protons but a different number of neutrons are called isotopes.
- Some isotopes have an unstable nucleus. They try to rearrange themselves into a more stable configuration by emitting energy or particles which we call radiation.
- Isotopes that emit ionizing radiation are called radioactive.
- This slide shows isotopes of hydrogen. Of these, H-3, or tritium, is radioactive.



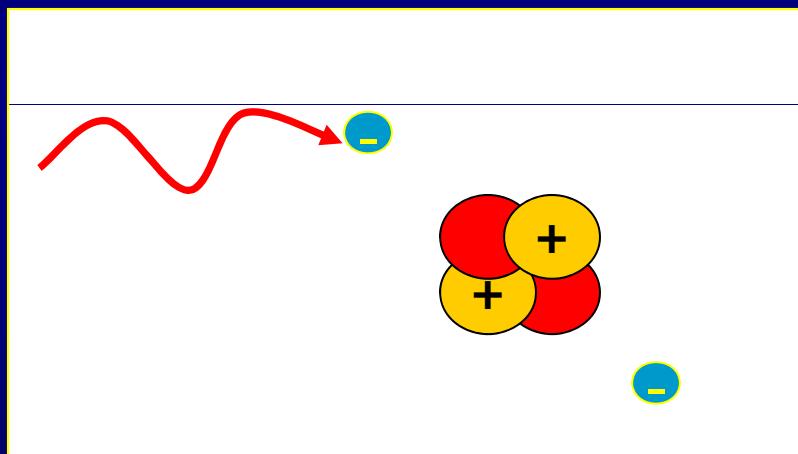
# Radioactive Decay

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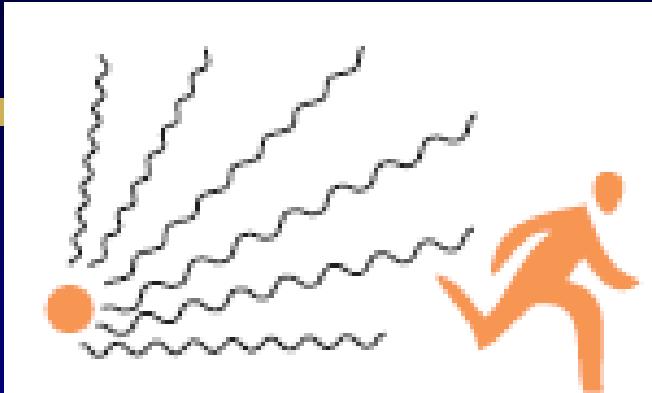
- Radioactive decay is a spontaneous change in the nucleus of an unstable atom
- Accompanied by the release of ionizing radiation in the form of particles or energy
- May result in the formation of new elements (either stable or unstable)
- Nuclear instability is related to either the neutron-to-proton ratio being too high or too low, or the nucleus being in an excited state (excess energy)

# Ionizing Radiation

- Radioactive decay releases ionizing radiation
- Ionizing radiation is energetic enough to remove orbital electrons from atoms or molecules with which it interacts.



- Non-ionizing radiation (e.g., visible light, microwaves) does not have sufficient energy to remove orbital electrons from the atoms with which it interacts.

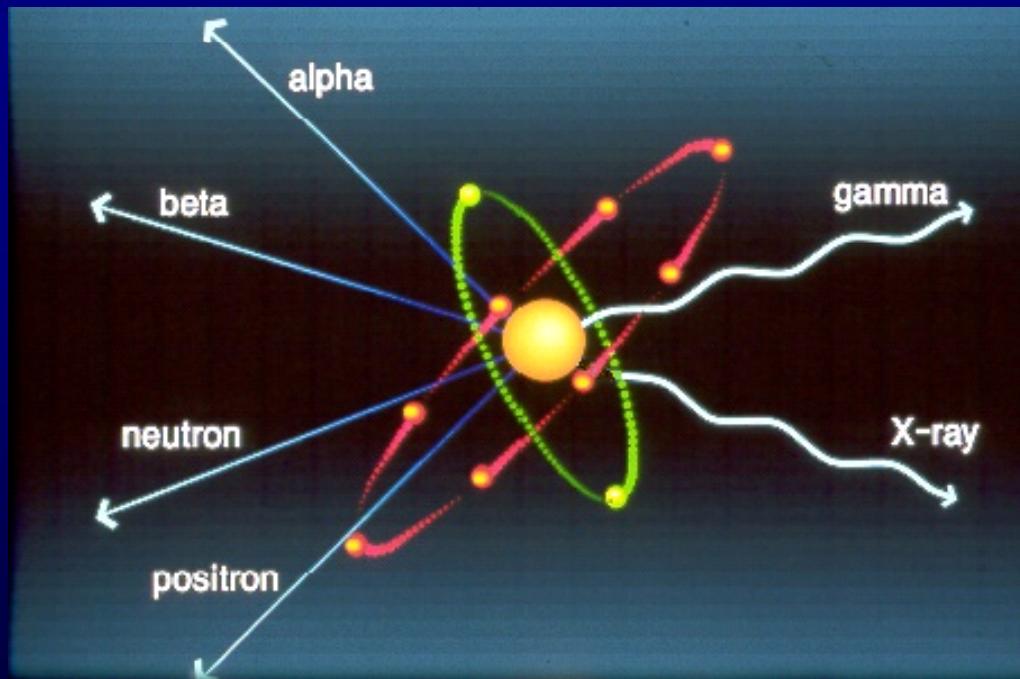


# Radiation vs. Contamination



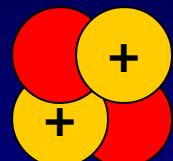
# Types of Ionizing Radiation

- Ionizing radiation can be in the form of particles or electromagnetic waves (photons).
- The particulate forms are alpha, beta, neutrons, and positrons.
- The non-particulate forms are gamma rays and X-rays.



# Alpha Radiation ( $\alpha$ )

- Alpha particles consist of two protons and two neutrons.
- Heavier atoms such as transuranics emit alpha particles.
- Because of their double positive charge and relatively large size, alpha particles are slow (< 2E9 cm/sec) and have a limited range – no more than a couple of inches in air. They ionize other atoms by removing orbital electrons and can create relatively high numbers of ionizations in a very small volume.
- Alpha particles are not a hazard if they are outside of the body (cannot penetrate the skin's dead layer), but can cause a lot of damage if they enter your body.

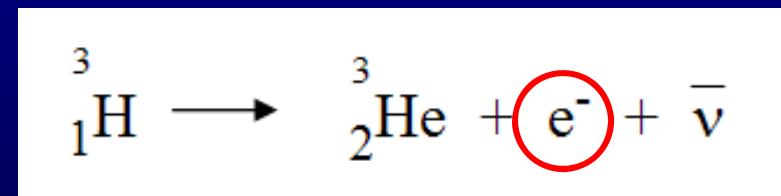
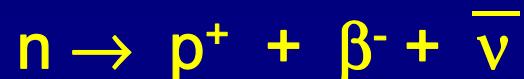


# Beta Radiation ( $\beta^-$ )

- Beta radiation is also particulate. A beta particle is the same as an electron and has a single negative charge.
- Since they are less massive than alpha particles and have less charge, they travel much faster and further in material. The distance depends upon their energy.
- An energetic (~1 MeV) beta particle travels near the speed of light (3E10 cm/s), up to 12 feet in air, and has the ability to penetrate the skin and the lens of an eye.

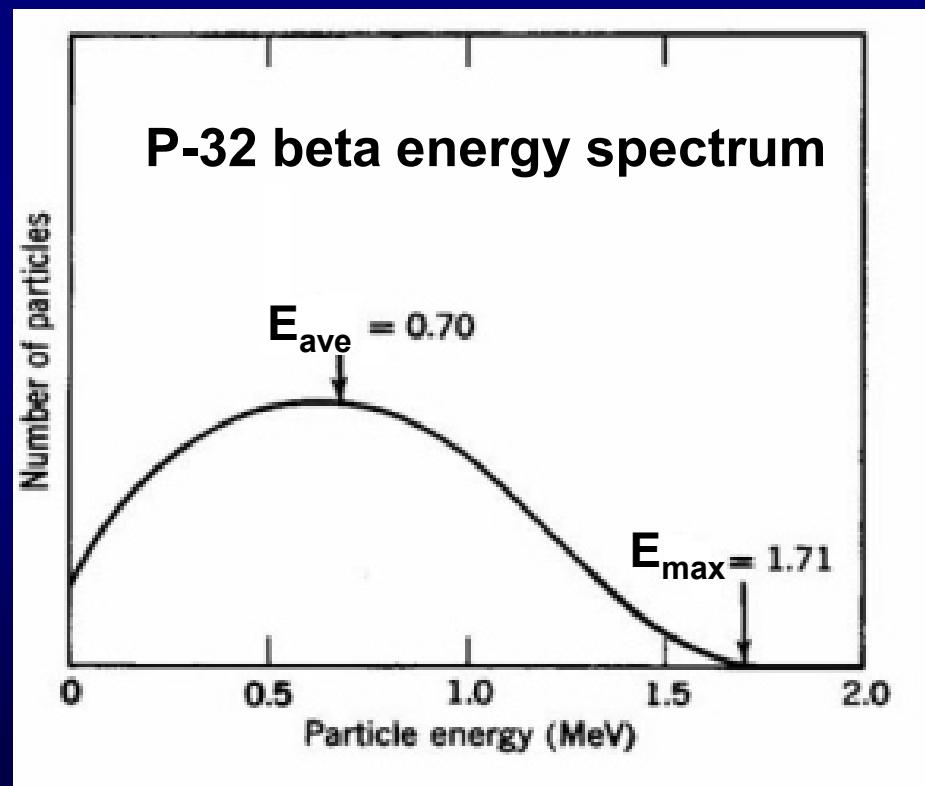
# Beta Emission

- Emission of an electron from the *nucleus* of a radioactive atom
- Occurs when neutron to proton ratio is too high, i.e., a surplus of neutrons:

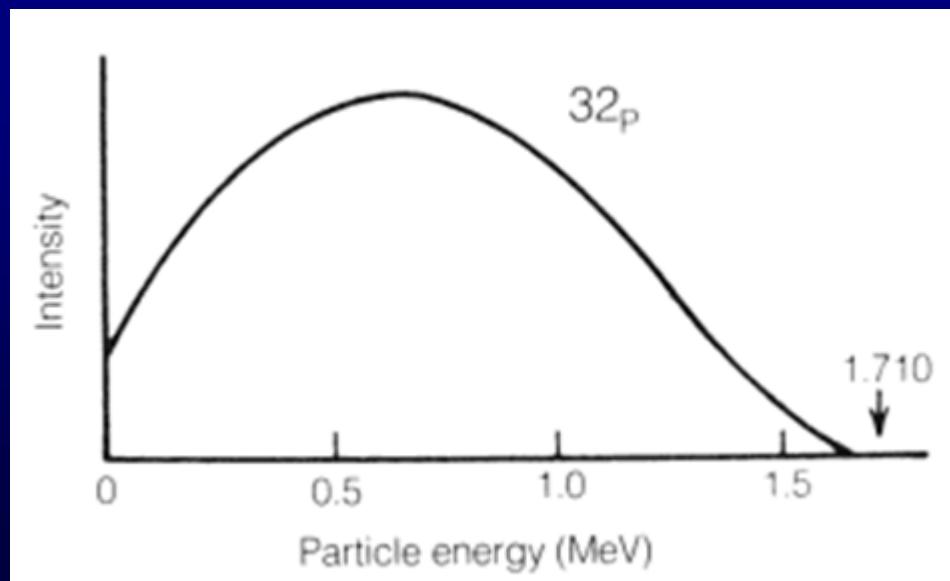
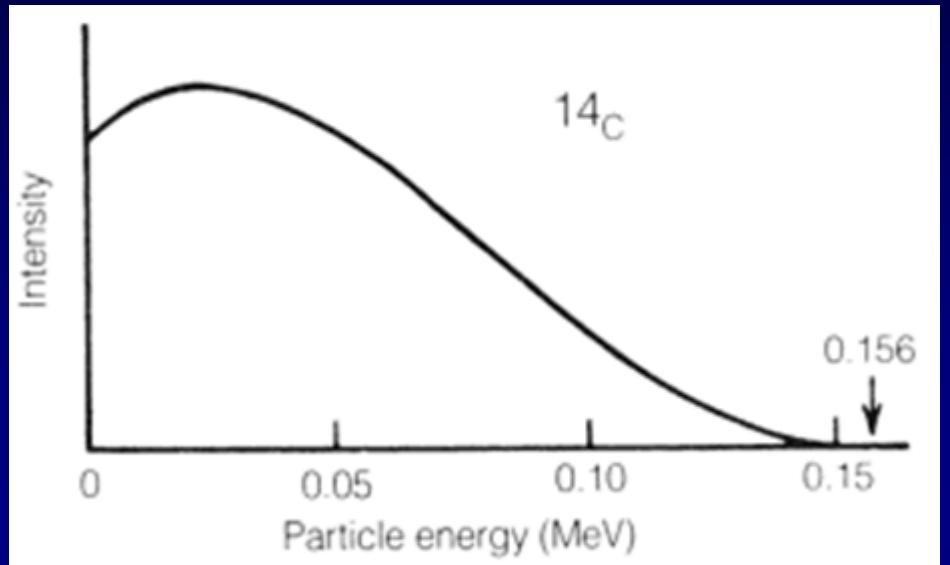
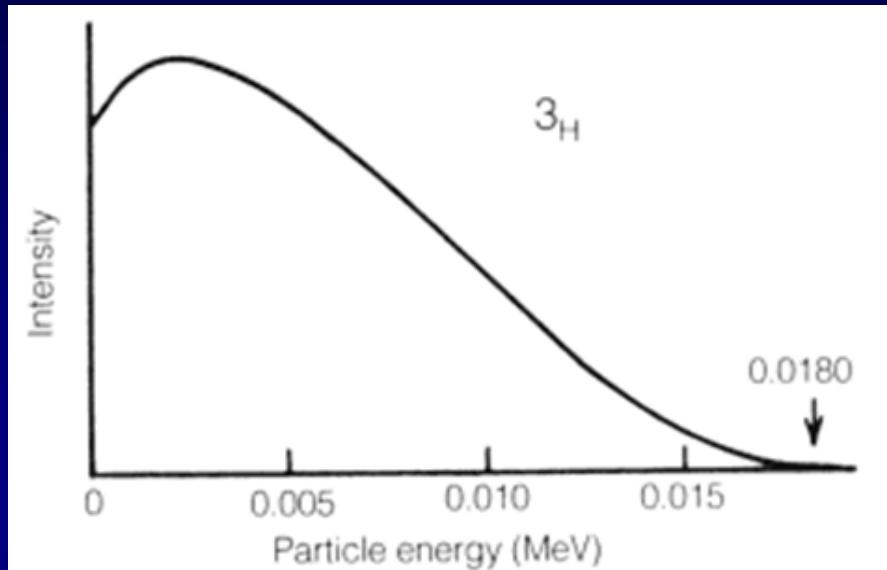


# Beta Energy Spectrum

Beta particles are emitted with a spectrum of energies (unlike alpha particles) since their energy is shared with an antineutrino.

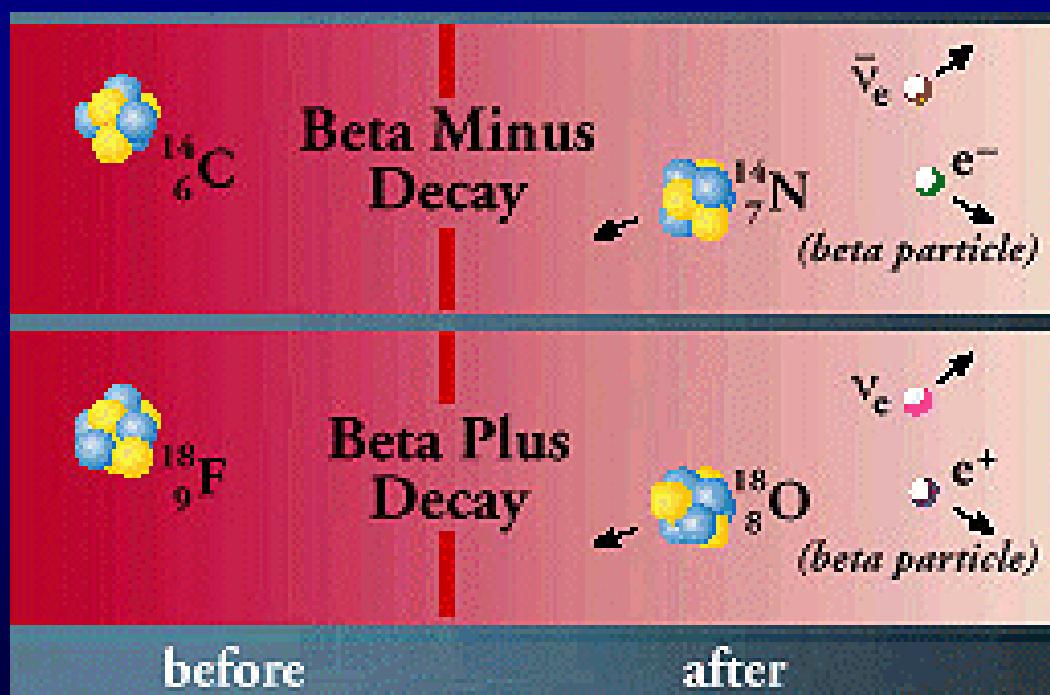


# Additional Beta Spectra



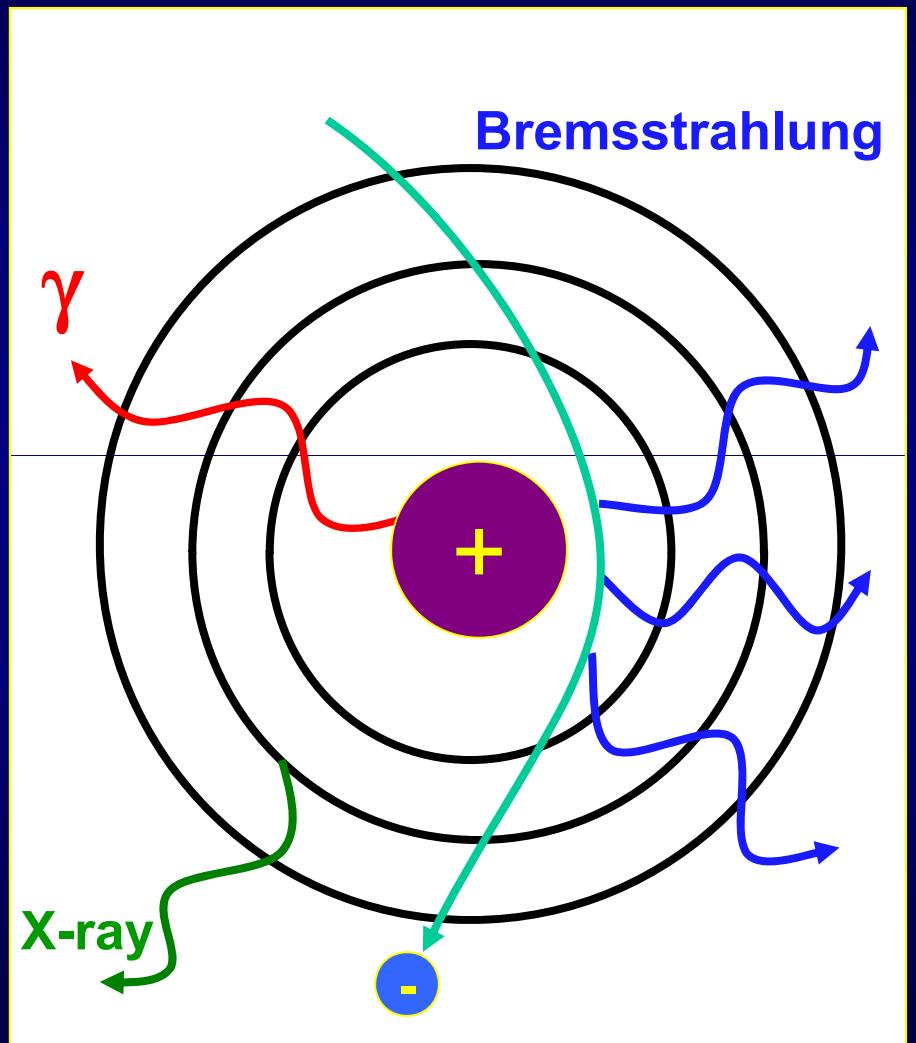
# Positron ( $\beta^+$ ) Radiation

- Occurs when the nucleus contains too many protons (neutron to proton ratio is too low)
- Nucleus emits a positron (a beta particle with a positive charge) and a neutrino  $p^+ \rightarrow n + \beta^+ + \nu$



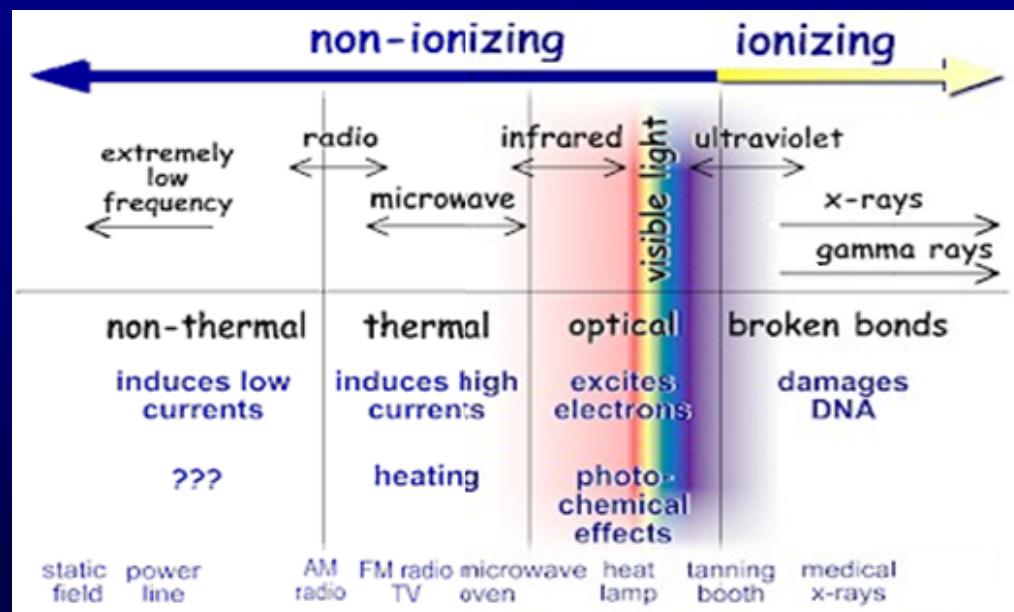
# Photon Emissions

- Photons,  $\gamma$ , have no mass or charge - they are pure energy.
- Characteristic X-rays are produced outside of the nucleus.
- Gamma rays originate in the nucleus of a radioactive atom.
- Bremsstrahlung photons are emitted when an electron is deflected by a nucleus.



# Gamma and X-ray radiation

- Photons (electromagnetic radiation) are grouped by wavelength. The shorter the wavelength, the higher the energy.
- Not all forms of radiation are ionizing.
- No defined energy cut-off between x-rays and gamma rays



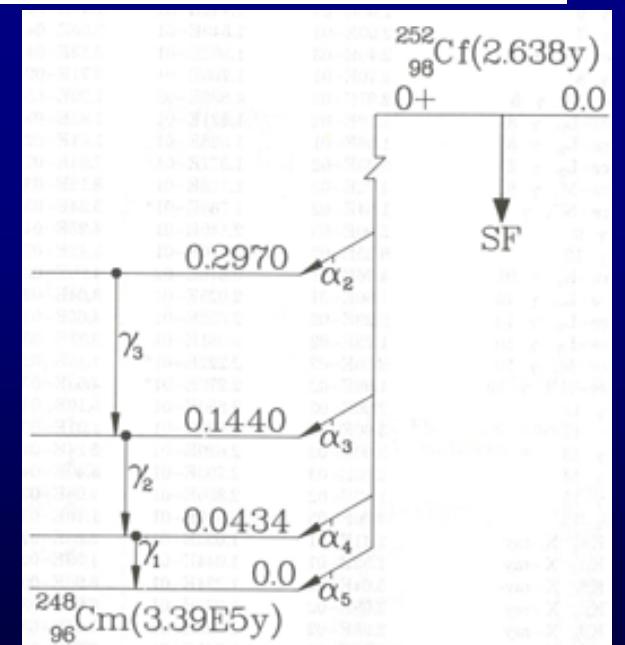
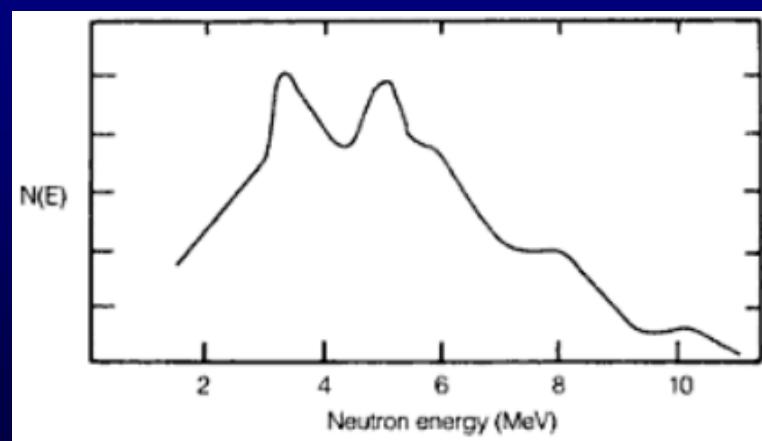
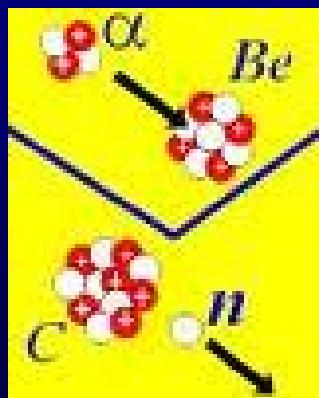
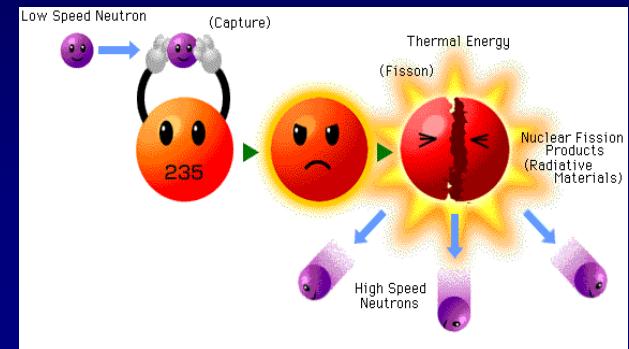
# Gamma Rays

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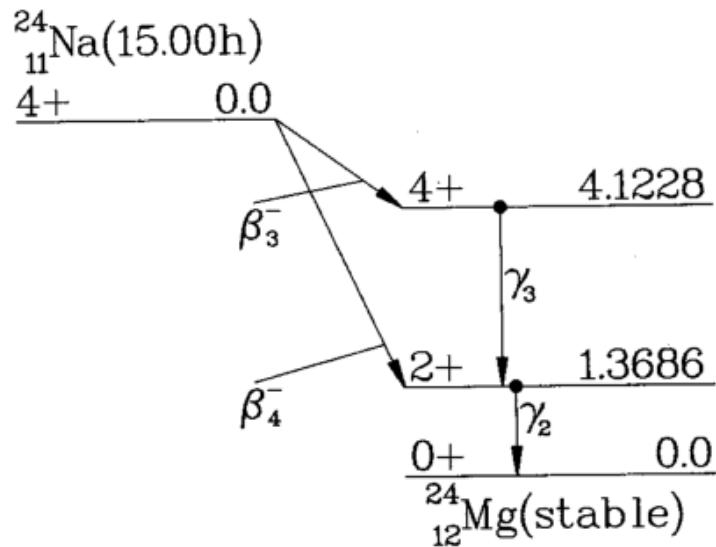
- Gamma rays are photon usually emitted from the nucleus of an atom following radioactive decay to rid the nucleus of excess energy
- Gamma rays are electromagnetic radiation just like visible light and UV rays, but they are more penetrating
- Gamma rays have characteristic energies that can be used to identify the radionuclide, e.g., Cs-137 decay results in the emission of 662 keV gamma rays

# Neutrons

- Neutrons are particulate radiation with no charge.
- Neutrons are generated through:
  - fission in a reactor
  - decay via spontaneous fission (
  - neutron generators (deuterons into a tritium target: 14 MeV)
  - alpha – neutron interaction



## Decay scheme example



### 11-SODIUM-24

HALFLIFE = 15 HOURS  
DECAY MODE(S):  $\beta^-$

13-OCT-77

RADIATION	y(i) (Bq-s) <sup>-1</sup>	E(i) (MeV)	y(i)×E(i)
$\beta^-$ 3	9.99E-01	5.537E-01*	5.53E-01
$\gamma$ 2	1.00E 00	1.369E 00	1.37E 00
$\gamma$ 3	9.99E-01	2.754E 00	2.75E 00

LISTED X, $\gamma$ AND $\gamma\pm$ RADIATIONS	4.12E 00
OMITTED X, $\gamma$ AND $\gamma\pm$ RADIATIONS**	2.45E-03
LISTED $\beta$ , ce AND Auger RADIATIONS	5.53E-01
OMITTED $\beta$ , ce AND Auger RADIATIONS**	1.35E-04
LISTED RADIATIONS	4.67E 00
OMITTED RADIATIONS**	2.59E-03

\* AVERAGE ENERGY (MeV)

\*\* EACH OMITTED TRANSITION CONTRIBUTES <0.100% TO  $\Sigma y(i) \times E(i)$  IN ITS CATEGORY.

MAGNESIUM-24 DAUGHTER IS STABLE.

# Activity

---

- **Activity, A, is the term used to measure the decay rate of a radionuclide**
- **The activity of a sample is based on the total number of radioactive atoms, N, and the probability of each atom undergoing radioactive decay.**
- **The decay constant,  $\lambda$ , represents this probability and is dependent on the half-life of the nuclide.**

$$A = \lambda N$$

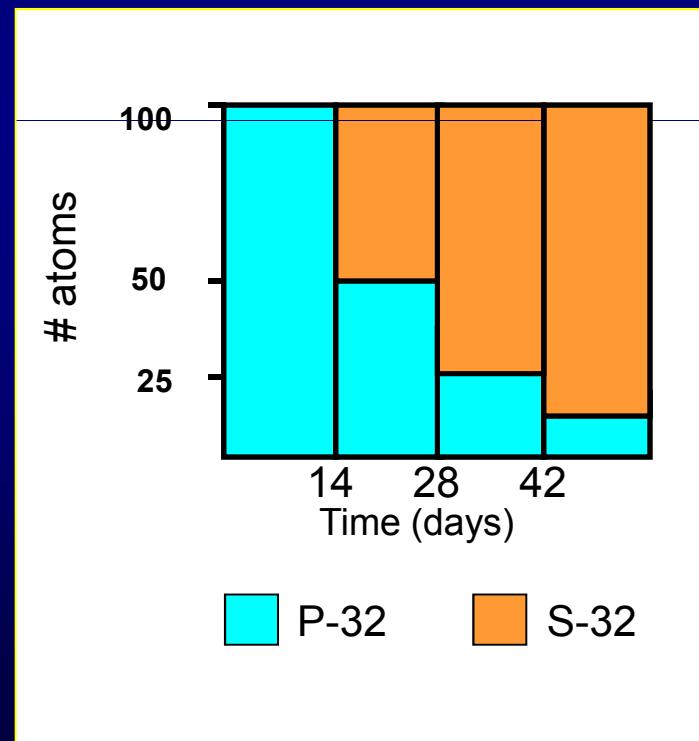
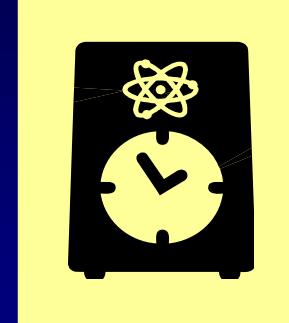
# Activity Units

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- Traditional unit is the curie, Ci  
 $1 \text{ Ci} = 3.7 \times 10^{10} \text{ dps}$  (disintegrations per second)
- SI (International System) unit is becquerel, Bq  
 $1 \text{ Bq} = 1 \text{ dps}$
- $1 \text{ Ci} = 3.7 \times 10^{10} \text{ dps} = 37 \text{ GBq}$

# Half-Life

- Half-life is the time required for half of the nuclei in a sample of radioactive material to undergo radioactive decay and is unique for each isotope.
- For example, radioactive P-32 decays with a half-life of 14 days to stable S-32.
  - Starting with 100 atoms of P-32
  - After 14 days,  $\frac{1}{2}$  of the atoms of P-32 will have decayed to S-32
  - After two half-lives, only 25 atoms of P-32 remain while the other 75 atoms are now S-32



# Half-Life and the Decay Constant

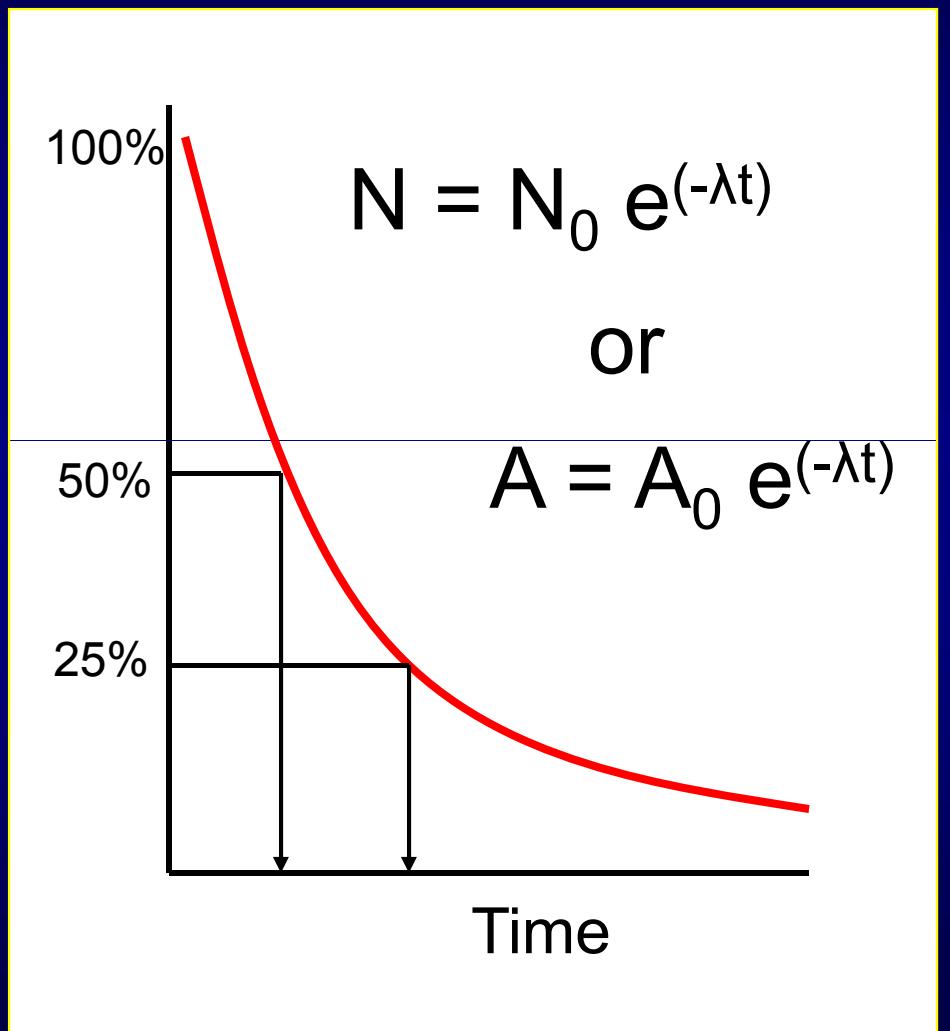
- Half-life,  $T_{1/2}$ , is directly related to the decay constant,  $\lambda$

$$T_{1/2} = \frac{\ln(2)}{\lambda} \quad \text{or} \quad \lambda = \frac{0.693}{T_{1/2}}$$

where  $\lambda$  is in units of inverse time (e.g.,  $s^{-1}$ )

# The Decay Equation

- Radioactive decay as a function of time decreases at a negative exponential rate.
- $N_0$  is the original number of radioactive atoms.
- N is the number remaining after time, t.
- This equation also applies to activity, A, as shown.
- The decay constant,  $\lambda$ , represents the probability that a radioactive atom will decay.



# Half-Life Example

A vial contains 1E6 atoms of Cs-137.

Cs-137 has a half-life of 30 years.

After 15 years, how many atoms of Cs-137 remain?

## 1) Using the Decay Equation:

$$N = N_0 e^{(-\lambda t)}$$

$$\lambda = \ln(2)/T_{1/2} = 0.693/T_{1/2}$$

$$\lambda = (0.693/30 \text{ y}) = 0.023 \text{ y}^{-1}, \text{ so}$$

$$N = (1E6 \text{ atoms})e^{[-(0.023 \text{ y}^{-1})(15 \text{ y})]}$$

$$N = 7.07E5 \text{ atoms}$$

## 2) Using simplified equation:

$$N = N_0(1/2)^n \quad \text{where } n = \text{number of elapsed half-lives}$$

15 years is  $\frac{1}{2}$  of the 30 year half-life of Cs-137

$$N = (1E6 \text{ atoms})(1/2)^{0.5} = 7.07E5 \text{ atoms}$$

# Specific Activity

- Specific Activity is the activity of a radionuclide per unit mass.

$$SA = A/\text{mass}$$

$$SA = \frac{(0.693/T_{1/2})(N)}{\text{mass}}$$

- To determine the mass, use the Atomic Mass of a radionuclide in units of g/mole

Note: The mole is a unit to determine the amount of a substance (6.02 E23 atoms/mole)



# Specific Activity Comparison

0.001 g



$^{60}\text{Co}$   
27

1 g

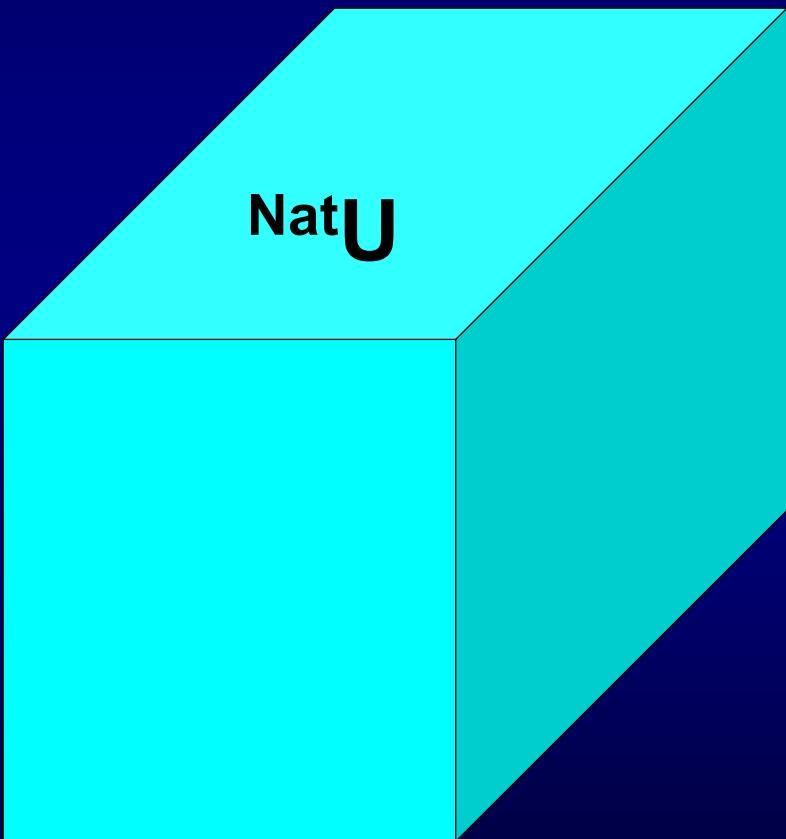


$^{226}\text{Ra}$   
88

1,428,571 g

Nat $\text{U}$

Amount in grams  
of each isotope  
equaling one curie  
of activity



# Serial Decay

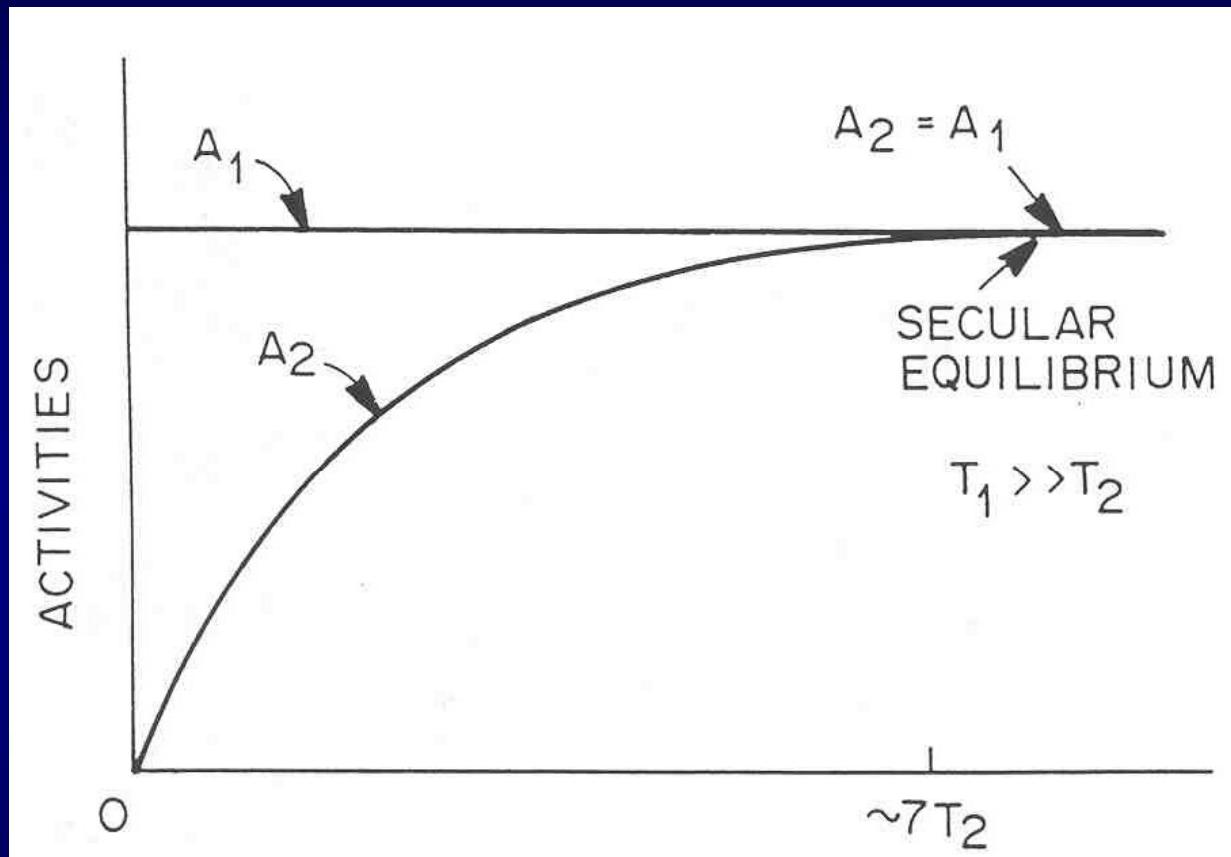
- Some radioactive isotopes decay into daughter products that are also radioactive. An example is the uranium-238 decay series.
- As seen within the U-238 series, decay occurs through different mechanisms – alpha, beta and gamma.
- Each isotope within a series has its own unique half-life which can vary from fractions of a second to billions of years.

URANIUM 238 (U238) RADIOACTIVE DECAY		
type of radiation	nuclide	half-life
α	uranium-238	4.47 billion years
β	thorium-234	24.1 days
β	protactinium-234m	1.17 minutes
β	uranium-234	245000 years
α	thorium-230	8000 years
α	radium-226	1600 years
α	radon-222	3.823 days
α	polonium-218	3.05 minutes
α	lead-214	26.8 minutes
β	bismuth-214	19.7 minutes
β	polonium-214	0.000164 seconds
α	lead-210	22.3 years
β	bismuth-210	5.01 days
β	polonium-210	138.4 days
α	lead-206	stable

# Equilibrium (Serial Decay)

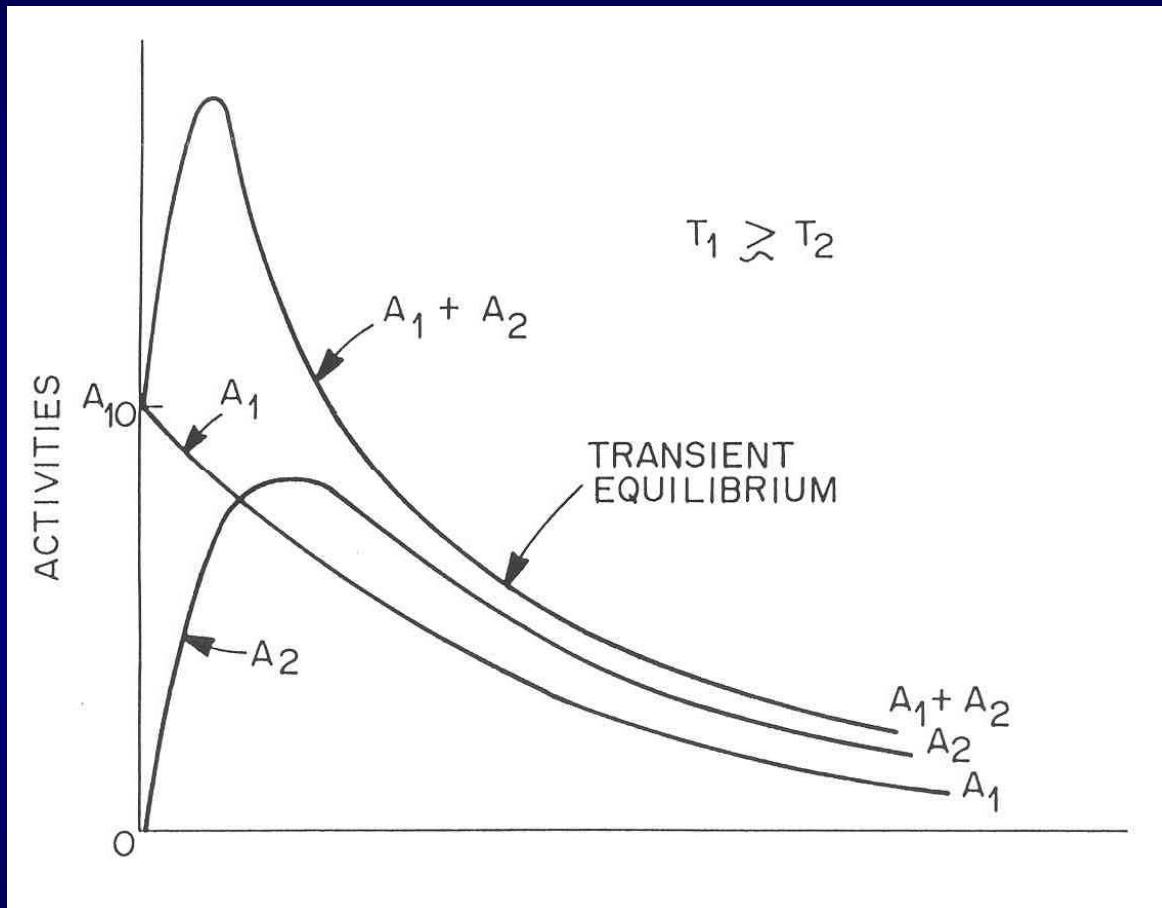
- Secular      Half-life of parent much greater (>100 times) than that of daughter products
- Transient      Half-life of parent only slightly greater (~10 times) than that of decay product
- No equilibrium      Half-life of parent less than that of progeny

# Secular Equilibrium



For example,  $\text{Sr-90} \rightarrow \text{Y-90}$   
 $T_1$  for Sr-90 = 29 years and  $T_2$  for Y-90 = 64 hours

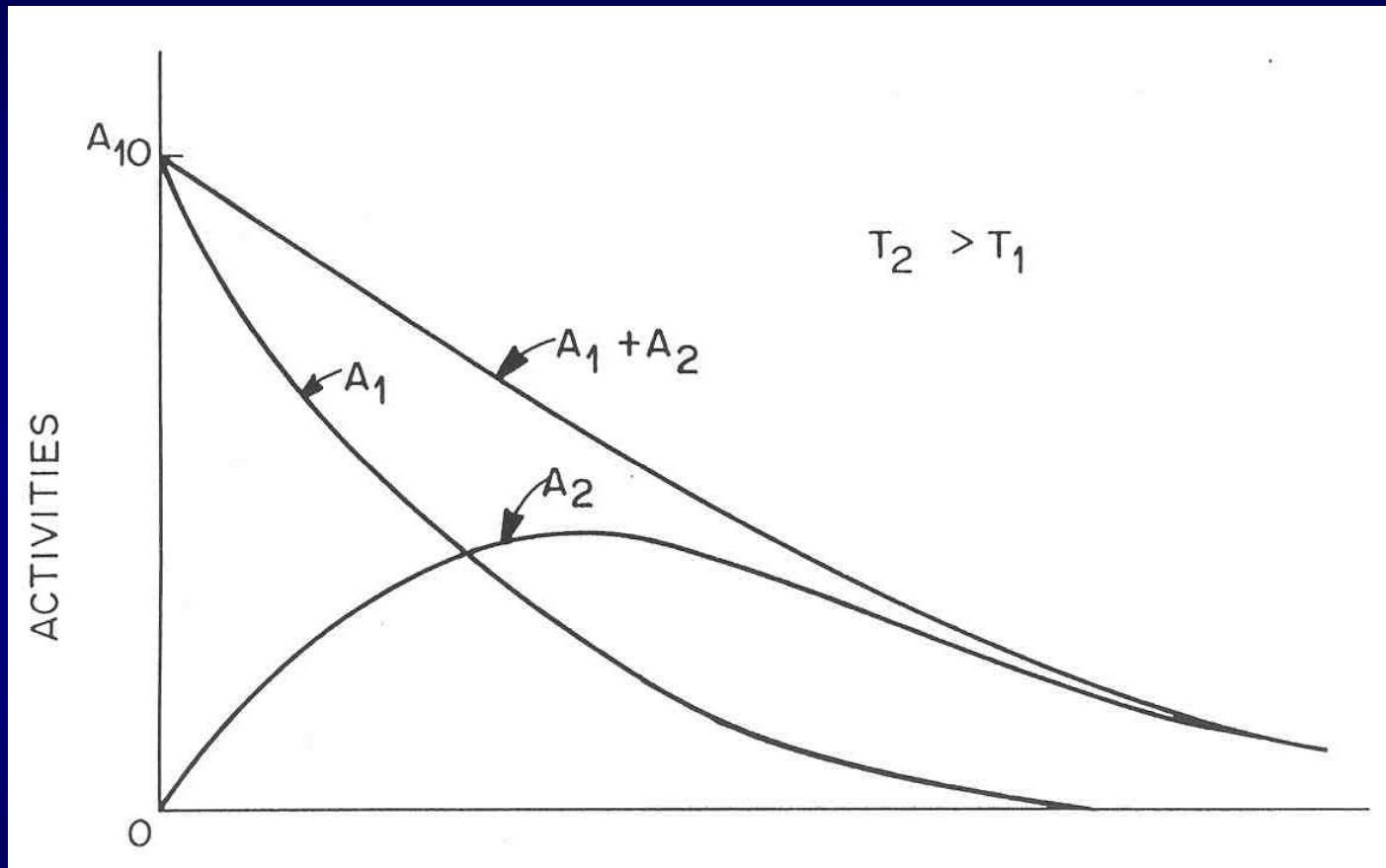
# Transient Equilibrium



For example,  $\text{Pb-212} \rightarrow \text{Bi-212}$

$T_1$  for Pb-212 = 10.6 hours and  $T_2$  for Bi-212 = 1 hour

# No Equilibrium



For example, Ce-146 → Pr-146  
T<sub>1</sub> for Ce-146 = 14 min and T<sub>2</sub> for Pr-146 = 26 min

# Radiation Quantities and Units

# Unit Prefixes

Tera	1E12	TBq
Giga	1E9	GBq
Mega	1E6	MBq
kilo	1E3	kBq
milli	1E-3	mCi
micro	1E-6	$\mu$ Ci
nano	1E-9	nCi
pico	1E-12	pCi

# Exposure

- **Exposure is related to the amount of energy transferred from photons (X-rays and gamma rays) to a given mass of air**
- **Exposure is typically measured in roentgens, R**
- **$1\text{ R} = 2.58\text{E-}4\text{ coulombs/kg}$   
 $= 87\text{ ergs/g}$**

**Note: No similar unit in the International System (SI)**

# Limitations of the Roentgen

---

- Roentgen applies only to photons
- Roentgen applies only in air
- Roentgen is defined only for photon energies up to 3 MeV

# (Limited) Use of the Roentgen

---

- Not used or defined in 10 CFR Part 20
- Not allowed as official record of dose (use rad or rem)
- Commonly found on survey instruments and used on radiation survey records

# Absorbed Dose

---

- The energy deposited by radiation in a given mass of any material
- Traditional unit is the rad  
 $1 \text{ rad} = 100 \text{ ergs/g}$
- SI unit is the gray, Gy  
 $1 \text{ Gy} = 100 \text{ rad}$
- Absorbed dose applies to all ionizing radiations at all energies in all media, including human tissue

# Roentgen and Rad Relationship

- Recall that an exposure of 1 R results in about 87 ergs/g in air
- Since 1 rad = 100 ergs/g
- Thus, in air,  $1 \text{ R} = 87 \text{ ergs/g} \times \frac{1 \text{ rad}}{100 \text{ ergs/g}} = 0.87 \text{ rad}$
- In human tissue, 1 R results in about 96 ergs/g
- Thus,  $1 \text{ R} = 0.96 \text{ rad}$  or ...

**$1 \text{ R} \approx 1 \text{ rad}$  for human tissue.**

# Limitations of the Rad

---

- Does not take into account differing biological effects of various types of radiations
- For example, in human tissue, 1 rad due to alpha exposure is NOT equal to 1 rad of beta exposure
- Since 1 rad from each radiation deposits the same amount of energy in tissue (100 ergs/g), the difference is related to energy distribution in tissue
- Thus, we need another factor that accounts for differing biological effects of the various types of radiation

# Quality Factor and Dose Equivalent

- Quality Factor,  $Q$ , is the modifying factor by which absorbed dose can be multiplied to account for differing biological effects
- Absorbed Dose  $\times Q =$  Dose Equivalent

Note that dose equivalent is only defined for human tissue

# Quality Factors (10 CFR 20.1004)

<u>Radiation Type</u>	<u>Quality Factor</u>
beta	1
gamma	1
X-ray	1
neutron	2–11 (depending on energy)
alpha	20

# Dose Equivalent

---

- Traditional unit for dose equivalent is rem
- Since  $Q = 1$  for photons and betas,  
1 rad of these radiations equals 1 rem
- SI unit is sievert, Sv  
 $1 \text{ Sv} = 100 \text{ rem}$
- $50 \text{ mSv} = \underline{\hspace{2cm}} \text{ mrem?}$

# Rule of Thumb

---

- For X-rays and gamma rays in human tissue:

$$1 \text{ R} = 1 \text{ rad} = 1 \text{ rem}$$

# Traditional Units and SI Units

Quantity	Traditional Unit	SI Unit	Conversion Factor
activity	curie (Ci)	becquerel (Bq)	$3.7 \times 10^{10}$ Bq/Ci
absorbed dose	rad	gray (Gy)	100 rad/Gy
dose equivalent	rem	sievert (Sv)	100 rem/Sv

**QUESTIONS?**

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**END OF  
HP FUNDAMENTALS**

# Review Questions

---

- What two particles in the atomic nucleus have the same mass?
- Atomic mass is the sum of the number of \_\_\_\_\_ and \_\_\_\_\_ in the nucleus.
- Isotopes of the same element have the same number of \_\_\_\_\_ but differ in the number of \_\_\_\_\_.
- What happens when ionizing radiation interacts with an atom?
- An alpha particle is the same as the nucleus of a \_\_\_\_\_ atom.

# Review Questions

---

- How far can an alpha particle travel in air?
- Can a beta particle penetrate your skin?
- How are X-rays similar to gamma radiation?
- What is the difference between gamma and an X-ray?
- Beta (-) particles are emitted by a nucleus that has too many \_\_\_\_\_ or too few \_\_\_\_\_.

# Review Questions

---

- What are the SI and traditional units of activity?
- After one half-life, how much of the radioactive material remains?
- If you have 1,600 MBq of an isotope with a half-life of 5 years, how much remains after 15 years?
- If you now have 800 mCi of an isotope with a half-life of 10 days, how much was there 20 days before?

# Review Questions

---

- What type of equilibrium condition exists when the daughter activity increases during in-growth to that of the parent nuclide?
- What type of equilibrium condition exists when the parent nuclide half-life is only slightly more than that of the daughter nuclide?
- What type of equilibrium condition exists between Ra-226 ( $T_{1/2} = 1,600$  y) decaying to Rn-222 ( $T_{1/2} = 3.8$  days)?
- What type of equilibrium condition exists when the half-life of the daughter product is more than that of the parent nuclide?

# Review Questions

---

- What two particles in the atomic nucleus have the same mass?
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# Review Questions

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- **What are the SI and traditional units of activity?**
- **After one half-life, how much of the radioactive material remains?**
- **If you have 1,600 MBq of an isotope with a half-life of 5 years, how much remains after 15 years?**
- **If you now have 800 mCi of an isotope with a half-life of 10 days, how much was there 20 days before?**

# Review Questions

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- What type of equilibrium condition exists when the daughter activity increases during in-growth to that of the parent nuclide?
- What type of equilibrium condition exists when the parent nuclide half-life is only slightly more than that of the daughter nuclide?
- What type of equilibrium condition exists between Ra-226 ( $T_{1/2} = 1,600$  y) decaying to Rn-222 ( $T_{1/2} = 3.8$  days)?
- What type of equilibrium condition exists when the half-life of the daughter product is more than that of the parent nuclide?